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# Multiscale Filamentary Structures in the Solar Corona and their Implications for the Origin and Evolution of the Solar Wind

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**Abstract.** A change in the paradigm of coronal structure has emerged as a result of definitive measurements made with radio occultation, white-light (SOHO/LASCO), ultraviolet (SOHO/UVCS), and soft X-ray (Yohkoh) measurements. The new paradigm is a direct result of measurements with unprecedented capabilities for detecting the faint, low-contrast, and small-scale raylike structures (striations, filamentary structures, flux tubes) that pervade the entire corona. The new measurements show that — contrary to the longstanding view that the boundaries of polar coronal holes diverge significantly beyond radial, evolving around the edges of coronal streamers — coronal holes extend into interplanetary space approximately radially. Within a few solar radii, coronal streamers evolve into the heliospheric current sheet, occupying only a small volume of interplanetary space, comprising the finest filamentary structures, and carrying the slowest solar wind. In the remaining vast regions of interplanetary space, a hierarchy of small-scale raylike structures follow open magnetic field lines, threading their way through closed field regions, to carry the imprint of the Sun (coronal hole boundary, active regions, and bright points) into interplanetary space. Rooted in small-scale features all over the Sun, the raylike structures span supergranular to kilometer scale sizes. The contrast of the raylike structures has a one-dimensional spatial wavenumber spectrum that is inverse power-law with a spectral index close to 5/3. Both coronal holes and the quiet Sun are sources of the fast solar wind.

## 1. Introduction

Our knowledge and understanding of the origin and evolution of the solar wind has been based mainly on relating solar measurements to *in situ* solar wind measurements conducted beyond 0.3 AU [*Zirker*, 1977; *Hundhausen*, 1977; *Munro and Jackson*, 1977; *Gosling*, 1995], with the *in situ* high latitude solar wind measurements by Ulysses having taken place at even larger distances from the Sun [*McComas et al.*, 1998]. For the first time, definitive measurements of the corona have been made, far enough away from the large-scale closed magnetic fields composing coronal streamers, and with enough sensitivity to detect faint, small-scale, and very low contrast structures. As a result, a fundamentally different view of the origin and evolution of the solar wind has emerged.

The purpose of this paper is to summarize the developments that have led to these surprising results. While ground-breaking radio occultation measurements have produced a new paradigm of coronal structure, they have also spurred synergistic studies based on ultraviolet, white-light, and soft X-ray measurements, fortuitously at a time when such measurements have been made with unprecedented capabilities by the SOHO (UVCS, LASCO) and Yohkoh (soft X-ray) missions.

We start this review with a brief description of radio occultation measurements. To provide context for the current progress, we also briefly summarize earlier results. Subsequent developments are described, and the latest results on the morphology of the coronal structure and the origin and evolution of the solar wind are summarized and discussed.

## 2. Radio Occultation Measurements

When a radio wave propagates through the corona, a wide variety of radio propagation and scattering phenomena caused by the solar wind plasma can be observed. These include intensity scintillation, angular broadening, phase or Doppler scintillation, spectral broadening, Faraday rotation, and others. Since such measurements take place when a natural radio source or a spacecraft transmitting radio signals passes behind the corona as observed from Earth, they are known collectively as radio occultation measurements. Radio occultation measurements of the corona observe electron density most directly, but they also yield information on solar wind velocity and magnetic field [*Jokipii*, 1973, *Bird and Edenhofer*, 1990, *Coles*, 1993]. Conducted for over four decades, they have produced considerable information on the radial, latitudinal, and in some cases, solar cycle dependence of these solar wind parameters; they have also established many characteristics of the electron density fluctuations near the Sun [see e.g., *Hewish*, 1972; *Jokipii*, 1973; *Bird and Edenhofer*, 1990; *Coles*, 1993; *Woo*, 1993a, *Grall et al.*, 1996].

By probing the solar wind before it evolves with heliocentric distance, radio occultation measurements provide a crucial link for understanding the connection between the Sun and interplanetary space. As path-integrated measurements, they also act as a natural bridge between solar and *in situ* solar wind measurements. While radio occultation measurements have served this role for many years in the study of transient phenomena, i.e., coronal mass ejections [*Woo et al.*, 1982; *Woo et al.*, 1985; *Woo and Schwenn*, 1991; *Woo*, 1997a], only recently have they contributed to our understanding of the quiescent corona and its extension into interplanetary space.

Doppler and ranging measurements using state-of-the-art radio systems are made by the NASA Deep Space Network for the purposes of precisely navigating interplanetary spacecraft; ranging gives distance of the spacecraft and Doppler its velocity. To distinguish these measurements from those that strictly observe scattering phenomena, e.g., intensity scintillation (or IPS for interplanetary scintillation), Doppler and ranging are sometimes referred to as radio propagation measurements. For the purpose of probing the solar corona, radio propagation measurements provide precise, highly sensitive, and wide dynamic range measurements of path-integrated density (ranging) and path-integrated density fluctuation (Doppler). In terms of imaging of the quiescent corona, ranging observes the brightness, and Doppler detects the contrast of the structures The unique abilities of radio propagation measurements allow them to sense structures that are smaller, fainter, of lower contrast, and farther away from the Sun (and hence farther away from closed field lines) than those by imaging instruments, and they are the reason for the recent breakthroughs in defining the quiescent corona [*Woo*, 1996b].

## 3. The Quiescent Corona

A systematic variation in radio occultation measurements of the quiescent corona — organized around the large-scale coronal magnetic field — was first revealed when Doppler scintillation measurements (sensing small-scale path-integrated electron density fluctuations) were normalized to heliocentric distance [*Woo and Gazis*, 1993; *Woo et al.*, 1995a]. Similar clues followed when the dominant radial dependence was removed from ranging measurements (sensing path-integrated density) [*Woo et al.*, 1995b; *Woo*, 1996c].

Further insight was provided by comparing the measurements of path-integrated density N and path-integrated density fluctuations $\Delta N$, showing that $\Delta N/N$ varied significantly throughout the solar corona [*Woo et al.*, 1995c]. Prior to these results, $\Delta N/N$ was thought to be constant, and measurements of $\Delta N$ were often assumed to serve as a proxy for N [*Erickson*, 1964, *Houminer and Hewish*, 1974, *Tappin*, 1986, *Woo and Gazis*, 1994]. Although there is evolution with heliocentric distance, similar variations in fractional density fluctuations are still evident in direct plasma measurements made at Earth orbit [*Huddleston et al.*, 1995].

As observed in solar eclipse pictures, with increasing heliocentric distance, coronal streamers taper to narrow extensions of a couple of degrees in angular size with respect to Sun center, a feature that has been referred to as a streamer stalk [*Koutchmy and Lifshits*, 1992]. The identification of enhancements in Doppler scintillation measurements as streamer stalks [*Woo et al.*, 1995a, 1995b], and their subsequent confirmation with simultaneous SOHO white-light measurements [Habbal et al., 1997], marked an important breakthrough in the investigation of the quiescent corona using radio occultation measurements. Not only was this the first time that near-Sun radio occultation measurements had been connected to a coronal feature, it also revealed that the observed electron density variations could be caused by quasi-stationary filamentary or raylike structures (flux tubes, striations), as imagined in early studies of the solar wind [*Parker*, 1963], in addition to turbulent eddies convected along with the solar wind.

### 3.1 Raylike Structures

The new perspective of raylike structures paved the way for taking advantage of the extensive information available on electron density fluctuations deduced from phase scintillation, spectral broadening and angular broadening measurements, to demonstrate that the corona was permeated by a hierarchy of filamentary structures [*Woo*, 1996a], with the smallest about 1 km at the Sun, at least two orders of magnitude smaller than those observed by imaging instruments. It was possible to distinguish spatial from temporal variations because angular broadening observes spatial while phase scintillation detects temporal variations. It was possible to discriminate raylike structures from convected turbulence because the temporal variations mapped to spatial variations according to the rotation rate of the Sun, not the velocity of the solar wind [*Woo*, 1996a].

Two features of small-scale density fluctuations that have proven difficult to explain are the abrupt increase in anisotropy of the density irregularities close to the Sun [*Armstrong et al.*, 1990], and the break in the power spectrum describing the density fluctuations [*Coles et al.*, 1991]. The new paradigm of raylike structures not only elucidated the nature of the density fluctuations, it unified the extensive results on density fluctuations deduced from radio occultation measurements, showing that the anisotropy and spectrum break both represented manifestations of the detection of the smallest raylike structure in the corona [Woo 1996a; Woo and Habbal, 1997b].

In the outer corona, both ranging [*Woo and Habbal*, 1997a] and white-light [*Koutchmy*, 1977; *Woo et al.*, 1998] measurements show that the largest structures are several degrees in angular size measured with respect to Sun center. The largest structures consist of polar plumes — also found to originate from low-latitude coronal holes [*Woo*, 1996d] as well as the quiet Sun (regions on the Sun other than coronal holes and active regions) [*Woo and*

*Habbal*, 1997a; *Woo et al.*, 1998] — and streamer stalks, which are the brightest and have the highest contrast [Koutchmy, 1977; Guhathakurta and Fisher, 1995]. The contrast of the hierarchy of these coronal structures has a one-dimensional spatial wavenumber spectrum that is inverse power-law with an index of approximately 5/3, while the smaller turbulent eddies whose spatial wavenumber spectrum is also inverse power-law has a spectral index of approximately one [*Woo*, 1996a; *Woo and Habbal*, 1997b].

### 3.2 Coronal Streamers

Since streamer stalks are composed of filamentary structures that are finer [*Woo and Habbal*, 1997b], and have a contrast that is significantly higher [*Woo et al.*, 1995b; *Woo and Habbal*, 1997a] than that of the small-scale structures in the rest of the corona, they are also the most prominent feature in scintillation measurements. Streamer stalks are more conspicuous in scintillation than in path-integrated density measurements (white-light) because $\Delta N/N$ is enhanced inside them [*Woo et al.*, 1995b]. In the same way that the heliospheric current sheet provides context for *in situ* solar wind measurements, so does the streamer stalk for radio occultation measurements of the solar corona. Faraday rotation measurements show that magnetic field polarity reverses within streamer stalks, hence confirming that they are indeed the coronal manifestation of the heliospheric current sheet [*Woo*, 1997b], or more specifically the heliospheric plasma sheet [*Bavassano et al.*, 1997]. Intensity scintillation measurements show that systematic large-scale velocity structure overlies the streamer belt [*Woo*, 1995] and that streamer stalks are the elusive sources of the slow solar wind [*Woo and Martin*, 1997]. This latter result has since been strikingly confirmed by velocity estimates deduced from the SOHO UVCS Doppler dimming measurements [*Habbal et al.*, 1997].

### 3.3 Imprint of the Sun on the Solar Wind

Another surprise from radio occultation measurements has been the discovery that the boundary between polar coronal hole and coronal streamer at the Sun extends approximately radially into interplanetary space [*Woo and Habbal*, 1997a], rather than undergoing any significant divergence as previously thought [*Zirker*, 1977; *Munro and Jackson*, 1977; *Gosling et al.*, 1995]. This was revealed when ranging measurements of path-integrated density near 30 Ro were compared with white-light images by the Mauna Loa K-coronameter. Additional support for the radial preservation of the coronal hole boundary in the outer corona has been obtained from a similar comparison using SOHO LASCO white-light instead of ranging measurements [*Woo et al.*, 1998]. Comparison of the azimuthal profile of path-integrated density by ranging measurements near 30 Ro with that of polarized brightness pB measured by the Mauna Loa K-coronameter at 1.15 Ro [*Fisher et al.*, 1981] has revealed that the coronal hole boundary is not an isolated feature that extends radially, but is rather an integral part of the general coronal density profile that is preserved during radial expansion. This general coronal density profile includes the signatures of active regions and bright points. The imprint of these different density structures at 30 Ro can only be transported there by open magnetic field lines originating within these complexes.

Doppler scintillation, like soft X-rays compared with white-light, shows a significantly stronger relative enhancement than ranging over active regions [*Woo and Habbal*, 1998]. Since Doppler scintillation is a measure of the contrast in density across the filamentary structures, this may not be surprising because large temperature variations are observed in loops forming active regions [see e.g., *Arndt et al.*, 1994]. Furthermore, since the physical characteristics of bright points are similar to those of active regions [*Habbal*, 1994], it is not surprising that bright points are also manifested in interplanetary space.

### 3.4 Origin and Evolution of the Solar Wind

The almost radial expansion of the coronal density into interplanetary space implies that open field lines extend from the solar surface not only from coronal holes, but also from a significant fraction of the solar surface, namely the quiet Sun. This is consistent with the coexistence of closed and open field lines observed in high spatial resolution eclipse pictures [*Koutchmy and November*, 1996]. The emergence of open field lines from quiet region latitudes covering 30–60° coincides with the latitudes where Ulysses has measured fast solar wind [*McComas et al.*, 1998]. Upon close inspection of the Ulysses *in situ* measurements, it is clear that there is a slow yet systematic decline in the velocity from higher to lower latitudes, which can be accounted for by the change in coronal density from coronal holes to quiet regions [*McComas et al.*, 1998]. Closer to the Sun, latitudinal profiles of solar wind velocity in the corona deduced from SOHO/UVCS Doppler dimming measurements also indicate that the wind emerging from the quiet Sun is relatively fast [*Habbal et al.*, 1997a]. That fast wind originates from quiet regions as well as coronal holes first became evident from Doppler scintillation measurements, which indicated that the density fluctuations associated with the quiet Sun beyond the radial extension of the coronal hole were similar to those associated with the polar coronal hole [*Habbal et al.*, 1997a]. Taken together, the results from the radio occultation, ultraviolet, white-light, and *in situ* solar wind measurements strongly support the view that fast wind originates from both coronal holes and the quiet Sun.

## 4. Summary and Discussion

The new global view of the corona based on measurements conducted during solar minimum conditions can be summarized as follows. Bright large-scale coronal streamers dominate the corona at the Sun, giving the false impression of diverging polar coronal holes [*Woo et al.*, 1998]. Within a few solar radii, the streamers evolve into the heliospheric current sheet [*Woo*, 1997], occupying only a small volume of interplanetary space [*Wang et al.*, 1997], and carrying the slowest solar wind [*Habbal et al.*, 1997]. In the remaining vast regions of interplanetary space, a hierarchy of faint low-contrast raylike structures [*Woo*, 1996b; *Woo and Habbal*, 1997a] follow open field lines and thread their way through closed field regions, as have been observed in high spatial resolution white-light images [*November and Koutchmy*, 1996], to carry the imprint of the Sun approximately radially into interplanetary space. The raylike structures, rooted in small-scale features all over the Sun, span supergranular to kilometer scale sizes [*Newkirk and Harvey*, 1968; *Woo and Habbal*, 1997b].

In spite of evolution with heliocentric distance, there is evidence for the above picture in measurements of the solar wind beyond the 20–30 Ro region probed by the radio occultation measurements. Radially aligned structures have been observed in the inner heliosphere by Helios *in situ* plasma measurements [*Thieme et al.*, 1989, 1990]. When Yohkoh soft X-ray synoptic maps were correlated with IPS (interplanetary scintillation measurements that reflect density fluctuations) maps based on measurements by the Mullard Radio Astronomy Observatory in Cambridge, UK beyond 0.5 AU, a better match was found for the active regions than the heliospheric current sheet [*Hick et al.*, 1995]. The heliospheric current sheet is not detected by the Cambridge array, because the enhanced density fluctuations associated with the heliospheric current sheet span an angular size of only a few degrees [*Woo et al.*, 1995b, *Habbal et al.*, 1997], smaller than the spatial resolution of the Cambridge array. Although compressive fluctuations resulting from the dynamic interaction between slow and fast streams are present beyond 0.5 AU, as observed in IPS [*Ananthakrishnan et al.*, 1980] and Doppler scintillation [*Woo et al.*, 1995b] measurements, the correlation found between IPS and Yohkoh measurements indicates that some remnants of the imprint of the active region must also survive there.

The new view of the origin and evolution of the solar wind started with the realization that low frequency (less than 1 Hz) density fluctuations — long thought to represent convected inhomogeneities in phase/Doppler scintillation measurements [*Woo and Armstrong*, 1979, *Coles et al.*, 1991], and the least understood of solar wind fluctuations in terms of physical processes such as waves and turbulence [*Bavassano*, 1994; *Tu and Marsch*, 1995] — represented small-scale raylike structures [*Woo*, 1996a]. That the imprint of the Sun should extend into the solar wind is a consequence of these ubiquitous structures which provide the natural link between the Sun and the solar wind. That small-scale raylike structures should play a major role in the steady state solar wind is not surprising in light of the filamentary nature of the photospheric fields [*Almeida*, 1997]. Recent photospheric magnetic field observations have shown that individual elements come and go on very short time scales, with the flux on the surface, outside of active regions, being completely replaced every few days [*Title*, 1997].

The independent nature of the large-scale (coronal streamers) and small-scale (carrying the imprint of the Sun) density structures associated with the steady solar wind is not necessarily surprising. Differences between small- and large-scale solar magnetic fields have also been observed, with the large-scale field exhibiting a solar cycle dependence and the small-scale field none [*Harvey*, 1992, *Hoeksema*, 1997]. Differences have also been noted in the relationship of coronal mass ejections to small-scale structures such as sunspots, active regions or Hα flares, as opposed to large-scale magnetic structures such as streamers and prominences [*Hundhausen*, 1992]. It is clear that small-scale structures are a fundamental component of the solar wind, that they carry the imprint of the Sun to a large volume of interplanetary space, and that an understanding of coronal heating and acceleration of the solar wind cannnot be achieved without first understanding their role [*Habbal*, 1992].

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## References

Almeida, J.Sánchez, *Astrophys. J.*, **491**, 993, 1997.

Ananthakrishnan, S., W.A. Coles, and J.J. Kaufman, *J. Geophys. Res.*, **85**, 6025, 1980.

Armstrong, J.W., et al., *Astrophys. J.*, **358**, 685, 1990.

Arndt, M.B., S.R. Habbal, and M. Karovska, *Solar Phys.*, **150**, 165, 1994.

Bavassano, R., *Ann. Geophys.*, **12**, 97, 1994.

Bavassano, B., R. Woo, and R. Bruno, *Geophys. Res. Lett.*, **24**, 1655, 1997.

Bird, M.K., and P. Edenhofer, in *Physics of the Inner Heliosphere, Vol. 1*, eds. R. Schwenn and E. Marsch, 13, Springer-Verlag, Berlin, 1990.

Brueckner, G.E., et al., *Solar Phys.*, **162**, 357, 1995.

Coles, W.A., et al., *J. Geophys. Res.*, **96**, 1745, 1991.

Coles, W.A., in *Wave Propagation in Random Media (Scintillation)*, eds. V. Tatarskii, A. Ishimaru and V. Zavorotny, 156, SPIE, Bellingham, 1993.

Erickson, W.C., *Astrophys. J.*, **139**, 1290, 1964.

Fisher, R.R., et al., *Appl. Opt.*, **20**, 1094, 1981.

Gosling, J.T., et al., *Geophys. Res. Lett.*, **22**, 3329, 1995.

Grall, R., et al., *Nature*, **379**, 429, 1996.

Guhathakurta, M., and R. Fisher, *Geophys. Res. Lett.*, **22**, 1841, 1995.

Habbal, S.R., *Ann. Geophys.*, **10**, 14, 1992.

Habbal, S.R., *Space Sci. Rev.*, **70**, 37, 1994.

Habbal, S.R., et al., *Astrophys. J.*, **489**, L103,, 1997.

Harvey, K.L. in *Proceedings of SOLERS 22 Workshop*, ed. R.F. Donnelly, 113, 1992.

Hewish, A., in *Solar Wind Three*, NASA Special Pub. SP-308, 477, 1972.

Hick, P., et al., *Geophys. Res. Lett.*, **22**, 643, 1995.

Hoeksema, J.T., paper presented at the 1997 IAGA Meeting in Uppsala, Sweden, 1997.

Houminer, Z., and A. Hewish, *Planet. Space Sci.*, **20**, 1041, 1974.

Huddleston, D.E., R. Woo, and M. Neugebauer, *J. Geophys. Res.*, **100**, 19951, 1995.

Hundhausen, A.J., in *Coronal Holes and High Speed Wind Streams*, ed. J. Zirker, Associated University Press, Boulder, 225, 1977.

Hundhausen, A.J., *J. Geophys. Res.*, **98**, 13177, 1993.

Jokipii, J.R., *Ann. Rev. Astron. Astrophys.*, **11**, 1, 1973.

Koutchmy, S., *Solar Phys.*, **51**, 399, 1977.

Koutchmy, S., and M. Lifshits, *Space Sci. Rev.*, **51**, 61, 393, 1992.

McComas, D.J., et al., *Geophys. Res. Lett.*, **25**, 1, 1998.

Munro, R.H., and B.V. Jackson, *Astrophys. J.*, **213**, 874, 1977.

Newkirk, Jr., G., and J. Harvey, *Solar Phys.*, **3**, 321, 1968.

November, L.J., and S. Koutchmy, *Astrophys. J.*, **466**, 512, 1996.

Pätzold, M., et al., *Geophys. Res. Lett.*, **22**, 3313, 1995

Parker, E.N., *Interplanetary Dynamic Processes,* Interscience, New York, 1963

Tappin, S.J., *Planet. Space Sci.*, **34,** 93, 1986.

Thieme, K.M., R. Schwenn, and E. Marsch, *Adv. Space Res.*, **9**, 127, 1989.

Thieme, K.M., E. Marsch, and R. Schwenn, *Ann. Geophys.*, **8**, 713, 1990.

Title, A., et al., *EOS*, **79**, S289, 1998.

Tsuneta, S., et al., The soft-X-ray telescope for the Solar-A mission, Solar Phys., 136, 37, 1991.

Tu, C.-Y., and E. Marsch, *Space Sci. Rev.*, **73**, 1, 1995.

Wang, Y.-M., et al., *Astrophys. J.*, **485**, 875, 1997.

Woo, R., in *Wave Propagation in Random Media (Scintillation)*, eds. V. Tatarskii, A. Ishimaru and V. Zavorotny, 50, SPIE, Bellingham, 1993a.

Woo, R., *J. Geophys. Res.*, **98**, 18999, 1993b.

Woo, R., *Geophys. Res. Lett.*, **22**, 1393, 1995.

Woo, R., *Nature*, **379**, 321, 1996a.

Woo, R., in *Solar Wind Eight,* eds. D. Winterhalter, J. Gosling, S.R. Habbal, W. Kurth, and M. Neugebauer, American Institute of Physics, 38, 1996b.

Woo, R., *Astrophys. J.*, **458**, L87, 1996c.

Woo, R., *Astrophys. J.*, **464**, L95, 1996d.

Woo, R., in *Coronal Mass Ejections, Geophys. Monogr. 99*, ed. by M. Crooker, J.A. Joselyn, and J. Feynman, 235, AGU, Washington DC, 1997a.

Woo, R., *Geophys. Res. Lett.*, **24**, 97, 1997b.

Woo, R., and J.W. Armstrong, *J. Geophys. Res.*, **84**, 7288, 1979.

Woo, R., and J.W. Armstrong, *Nature*, **84**, 292, 1981.

Woo, R., and P.R. Gazis, *Nature*, **366**, 543, 1993.

Woo, R., and P.R. Gazis, *Geophys. Res. Lett.*, **21**, 1101, 1994.

Woo, R., and S.R. Habbal, *Geophys. Res. Lett.*, **24**, 1159, 1997a.

Woo, R., and S.R. Habbal, *Astrophys. J.*, **464**, L139, 1997b.

Woo, R., and S.R. Habbal, *Astrophys. J. Lett.*, in press, 1998.

Woo, R., and J. Martin, *Geophys. Res. Lett.*, **24**, 2535, 1997.

Woo, R., and R. Schwenn, *J. Geophys. Res.*, **96**, 21227, 1991.

Woo, R., et al., *Nature*, **300**, 157, 1982.

Woo, R., et al., *J. Geophys. Res.*, **90**, 154, 1985.

Woo, R., J.W. Armstrong, and P.R. Gazis, *Space Sci. Rev.*, **72**, 223, 1995a.

Woo, R., et al., *Astrophys. J.*, **449**, L91, 1995b.

Woo, R., et al., *Geophys. Res. Lett.*, **22**, 329, 1995c.

Woo, R., et al., *Astrophys. J.*, in press, 1998.

Zirker, J.B., ed., *Coronal Holes and High Speed Wind Streams*, Associated University Press, Boulder, 1977.